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Instrument Description of the Airborne Microwave Temperature Profiler

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The microwave temperature profiler (MTP) is a passive microwave radiometer installed in the NASA ER-2 aircraft and used to measure profiles of air temperature versus altitude. It operates at 57.3 and 58.8 GHz, where oxygen molecules emit thermal radiation. Brightness temperature is measured at a selection of viewing elevation angles every 14 s. MTP was the only remote sensing experiment aboard the ER-2 during the Airborne Antarctic Ozone Experiment. This paper describes hardware, calibration, and performance aspects of the MTP.

1. INTRODUCTION

The microwave temperature profiler (MTP) was constructed by the Jet Propulsion Laboratory (JPL) for the purpose of measuring profiles of air temperature versus altitude from the ER-2 aircraft. This instrument is the only airborne instrument of its kind that is currently in use.

MTP measures thermal emission from oxygen molecules at a selection of 10 elevation angles. Remote sensing at MTP frequencies provides observed quantities that contain information about the temperature of the air along the viewing direction. These observed quantities are converted to air temperature versus altitude after the flight using an algorithm to be described later. The altitude coverage is from about 2 km below the aircraft to 3 km above, for typical flight altitudes (60,000 ft, or 18,288 m). Air temperature estimates are made for 15 altitudes within this altitude region. Temperature profiles are obtained for every 14 s of flight.

The present MTP instrument was built for use by the Stratospheric-Tropospheric Exchange Project (STEP). The STEP flight series culminated in a tropical campaign flown from Darwin, Australia, in 1987, under the scientific direction of E. F. Danielsen. MTP is one of several STEP instruments on the ER-2 that were chosen for inclusion on the Airborne Antarctic Ozone Experiment (AAOE), which was conducted in August and September of 1987.

The success of the ER-2 MTP instrument owes much to the technological innovations that were developed with predecessor airborne temperature profiler systems. The predecessor to MTP was flown in the NASA C-141 Kuiper Airborne Observatory [*Gary*, 1984]. It was used from 1981 to 1984 to evaluate the merits of providing flight level change advisories to pilots for avoiding encounters with clear air turbulence (CAT), which is produced within recognizable temperature field structures. The predecessor to the C-141 instrument was built in 1977 and was installed in the NASA CV-990 aircraft for a CAT avoidance flight series in 1978 [*Gary*, 1981]. This instrument was used to demonstrate, for the first time, that passive microwave remote sensing techniques could be used to measure air temperature profiles from an aircraft. Both the CV-990 and C-141 instrument systems produced real-time graphic displays of temperature profiles during flight.

The observational goals for MTP were to (1) measure lapse rate for a 3000-ft-thick (914 m) layer (centered at the aircraft flight level) with a precision of 0.3 K/km and an accuracy of 1.0 K/km, and (2) measure altitude temperature profile structure using brightness temperature measurements, having a precision of 0.25 K, corresponding to at least 10 altitudes that cover a 2-km-thick layer of air (at typical flight levels). The lapse rates were intended for use in calculating potential vorticity (described below), and the altitude temperature profiles were intended for use in deriving altitude/flight path cross sections of potential temperature surfaces for the purpose of detecting and characterizing atmospheric waves. The instrument was to run automatically from only an on/off switch and provide a fail light in the cockpit. The MTP weight goal was to be well below 100 lb (45 kg) (the C-141 instrument weighed 450 lb (204 kg)). These goals for MTP have been met.

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2. SYSTEM OVERVIEW

MTP is a passive microwave radiometer that measures thermal emission from oxygen molecules located along a line-of-sight that is scanned in elevation angle. The instrument weights 58 lb (26 kg) and occupies a volume of 1.5 ft^3 (0.042 m^3). It is mounted in the ER-2 left wing Spearpod (which is one of the three types of wing pods that are flown on the ER-2).

The MTP instrument consists of two major assemblies, a sensor unit and a data unit, shown in Figure 1. The sensor unit is shown in greater detail in Figure 2 and is mounted on the outboard/front edge of the Spearpod. A fairing with a microwave transparent window offers a view of the air throughout a range of elevation angles in the forward direction. Figure 3 is a photograph showing the fairing and window. A horn antenna and reflector assembly are situated behind the window. A stepper motor rotates the reflector subassembly, which enables the reception pattern of the horn antenna to be directed to elevation angle viewing directions within the range −50° to +60°.

The superheterodyne radiometer in the sensor unit employs a single mixer and two local oscillators. The local oscillator (LO) frequencies are 57.3 and 58.8 GHz, which correspond to a wavelength of about 6 mm. A microprocessor turns on the LO sources one at a time, enabling measurements that are hereafter referred to as channel 1 and 2. A "total power" (i.e., not "Dicke switching") configuration is used.

The power entering the horn is linearly proportional to the "brightness temperature" in the viewing direction of the horn antenna. The proportionality of radio frequency (RF)

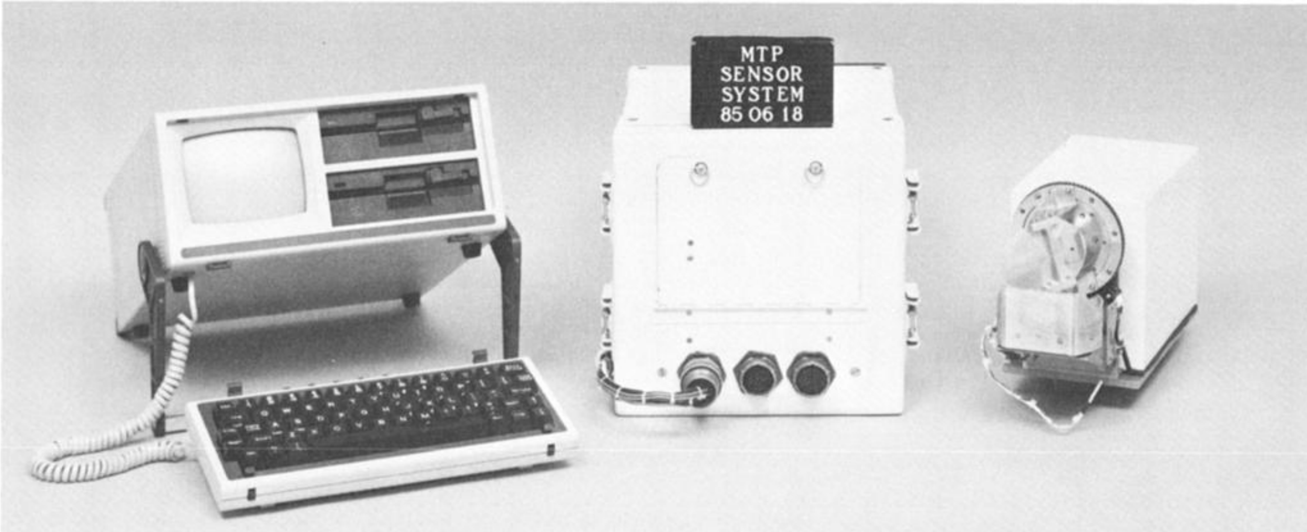

Fig. 1. Microwave temperature profiler components: data unit (middle) and sensor unit (right). Total weight is 58 lbs (26 kg), volume is 1.5 ft^3 (0.042 m^3). The microcomputer (left) can be used to check MTP performance before flights.

power level and brightness temperature is a consequence of the observing wavelength being at the long-wavelength side of the Planck blackbody radiation formula (where the Rayleigh-Jeans approximation applies). Hence the radiometer output level is related in a linear manner to brightness temperature, which is the parameter that is to be measured. There is an unknown quasi-constant term added to the radiometer output level, generated internally by MTP com-

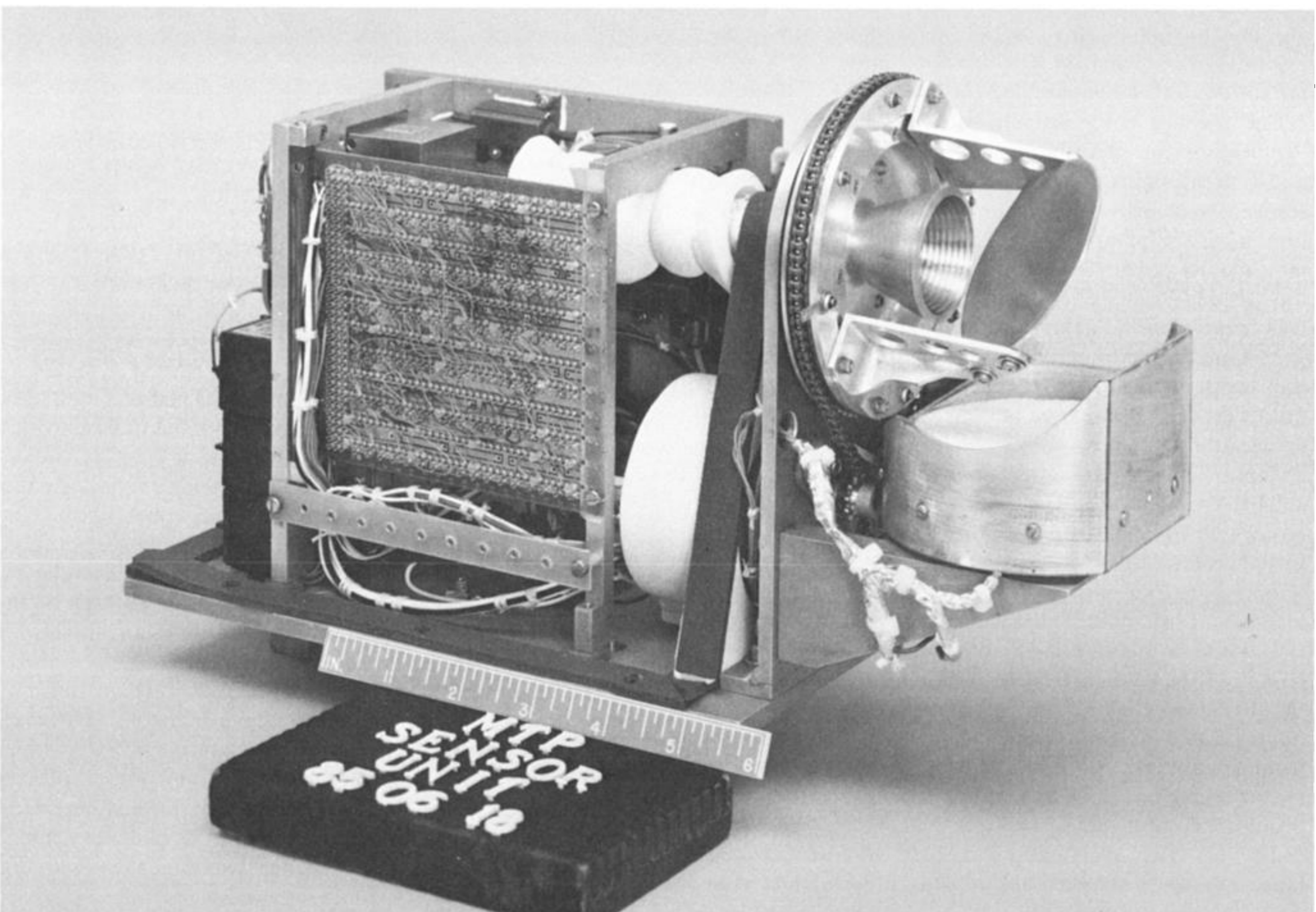

Fig. 2. Sensor unit with cover removed and electronics board hinged out. The corrugated horn and rotatable reflector are on the right, with the ambient calibration target underneath the reflector.

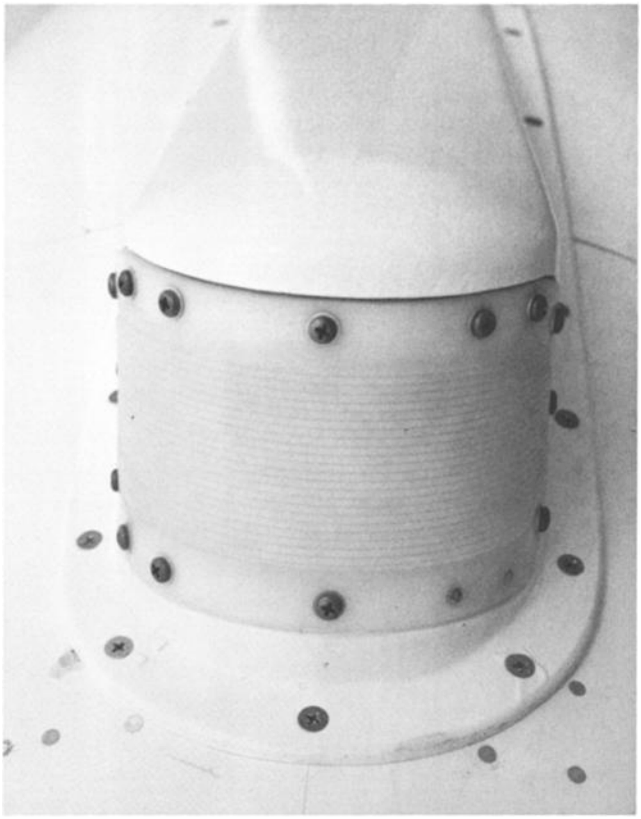

Fig. 3. Outer fairing and microwave-transparent window. The fairing protrudes 4 inches and is 16 inches long. The window has antireflection grooves on the outer and inner surfaces. The horn/reflector assembly is located behind the window.

ponents. This means that not only is it necessary to determine system gain (output counts/K), but it is also necessary to determine an offset, or an output level for a known brightness temperature.

The offset calibration is obtained by viewing an ambient target that is at a known physical temperature. The target used in MTP has a high microwave emissivity, which assures that its brightness temperature can be equated with its physical temperature. A thermistor temperature sensor is mounted in the target, and the target is allowed to change temperature as the environment temperature changes. This arrangement reduces the difference between the temperature of the target and the air outside the plane, which in turn reduces the influence of any gain inaccuracies.

The gain calibration is obtained by injecting a known amount of extra microwave energy in the waveguide immediately behind the horn antenna. This calibration signal is generated by a broadband noise diode, which has been calibrated using external hot and ambient calibration targets (described below). The noise diode exhibits a stability that is adequate for establishing system gain.

The data unit is shown in Figure 4. This unit contains a microprocessor that controls the stepper motor scanning mechanism (in the sensor unit). The microprocessor takes readings of the radiometer output and various MTP engineering temperatures and records these data on a cassette tape recorder. The data unit is connected to the aircraft via cables that provide electrical power, a time code, and synchro signals for aircraft altitude, roll, and pitch. Half the weight of the data unit consists of power supplies for converting aircraft power to dc and ac power needed by MTP components.

When the MTP is turned on from the cockpit, it automatically begins a series of 14-s observing cycles. A cycle consists of measuring the radiometer output from both channels for a sequence of viewing directions. There are 10 "sky" elevation angle views, and one directed at the ambient calibration target. At the calibration target position, the calibration noise diode is turned on to establish the radiometer gain for both channels.

The microprocessor records all raw data on the cassette tape recorder once each cycle. The raw data consist of the radiometer counts (for both channels) at the 10 sky positions and at the ambient target position (for the calibration noise diode turned off and on). Internal temperatures at selected MTP locations are also recorded for engineering and calibration purposes. The microprocessor also records a reading of its own internal clock, an aircraft clock signal, and readings of the aircraft synchro signals corresponding to altitude, roll, and pitch.

The cockpit control panel has two switch settings for MTP: standby and on. When the left wing pod power is turned on, MTP is put in "standby" mode. In this mode the MTP thermal control is enabled and monitored by the microcontroller. If a failure is detected, it is recorded on tape, and a "failure" indicator lamp on the pilot's console is illuminated. When the pilot switches MTP from "standby" to "on," the MTP microcontroller begins automatic observing. MTP can be switched to "standby" at any time during flight, and when it is turned to "on," at some later time, data recording will resume on the tape without erasing previously recorded data.

3. SENSOR UNIT

The sensor unit weighs 12 lb (5 kg) and has the dimensions $13 \times 7.5 \times 5$ inches. It consists of a microwave horn antenna and reflector assembly, an ambient calibration target, microwave waveguide components, a microwave receiver, and heaters with a proportional thermal control circuit. Figure 5 (upper section) is a block diagram that shows the major components of the sensor unit.

The antenna consists of a corrugated scalar feed horn which illuminates a rotatable offset parabolic reflector. This system produces an antenna pattern that has a beamwidth (half-intensity full-width) of 7.5° at the operating frequencies. The reflector protrudes through an opening in the skin of the pod which is enclosed by the fairing and microwave window. The antenna pattern is scanned along a 110° arc that extends from 50° below the forward (flight) direction to 60° above. The elevation step quantization is 0.21°.

The microwave window was constructed from a sheet of 1/4-inch-thick high-density polyethylene. The outer and inner surfaces are grooved in orthogonal directions which act as a 1/4-wave antireflection surface. They are 0.045 inch deep, 0.028 inch wide, and spaced 0.090 inch apart. The total window losses, due to reflection plus absorption, have been measured for all viewing directions and average 0.9% and 1.2% for channels 1 and 2, respectively. The maximum excursion from these averages for the various viewing directions is 0.5% and 0.7%, for channels 1 and 2. The tempera-

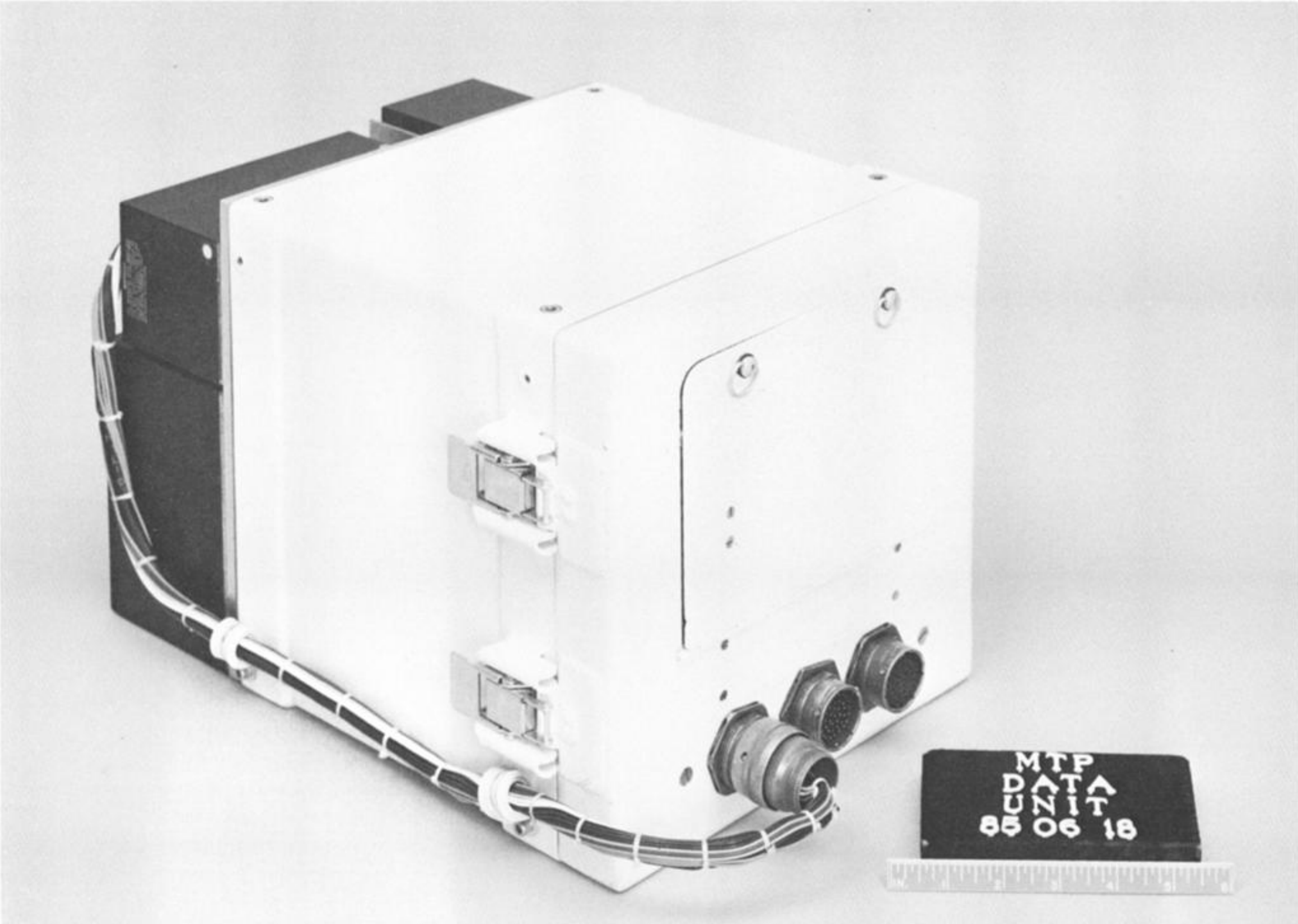

Fig. 4. Data unit, showing tape cassette flap door on front and power supplies at rear.

ture of the window is measured and recorded to enable corrections to be made for window losses.

The horn antenna is connected to a thermally insulated section of stainless steel waveguide. This waveguide provides thermal isolation of the mixer and receiver electronics from the horn antenna, which can be as cold as −65°C. The stainless steel waveguide section is followed by a cross-guide directional coupler which allows injection of the broadband noise diode calibration signal.

A waveguide isolator is situated between the cross-guide coupler and the input to the receiver for the purpose of reducing the level of unwanted LO reflections. The receiver (manufactured by Spacek Labs, Santa Barbara, California) consists of three major components: a broadband microwave mixer, a diode detector, and an intermediate frequency (IF) amplifier. The receiver has a 3.8- and 4.2-dB double-sideband noise figure, for channels 1 and 2, respectively. The mixer combines one of the Gunn diode LO signals (either 57.3 or 58.8 GHz) with the RF signal, and produces an IF signal. The mixer output is amplified by a low-noise IF amplifier. The IF passband is an important characteristic of MTP, because of "transparency correction" considerations (discussed by *Gary* [1989]). The IF passband extends from 200 to 400 MHz (half-intensity points).

The IF signal is converted to a dc voltage by a diode detector. Linearity is assured by operating the detector at a power level in the "square law" region of the detector, where its output is linearly proportional to the IF input power level. A stable dc amplifier prepares this signal voltage for input to a 100-kHz (maximum output frequency) voltage-to-frequency converter, which sends a train of pulses to a 16-bit counter in the data unit. The counter is interfaced with a programmable microcontroller, also located in the data unit, which specifies that counting occur for 255 ms.

This method of conveying the radiometer output to a data system has proven to be better than the more conventional alternative method of coupling the radiometer output voltage to an analog-to-digital converter in the microcontroller via a long cable. Experience with predecessor aircraft radiometers has shown that greater noise immunity is achieved by digitizing the radiometer output within the sensor unit.

The mixer, local oscillators, IF and dc amplifiers, and detector are mounted on an aluminum plate which is temperature controlled to 20.6° ± 0.1°C. Feedback thermistors are located on strategic components to sense temperature and regulate current to a 50-W heater controlled by a circuit that employs zero-crossing solid-state relays. This precaution minimizes switching "spikes" on the power bus.

4. DATA UNIT

The data unit weighs 46 lb (21 kg). and has dimensions 18 × 10.3 × 10.3 inches. It is located in the center of the left

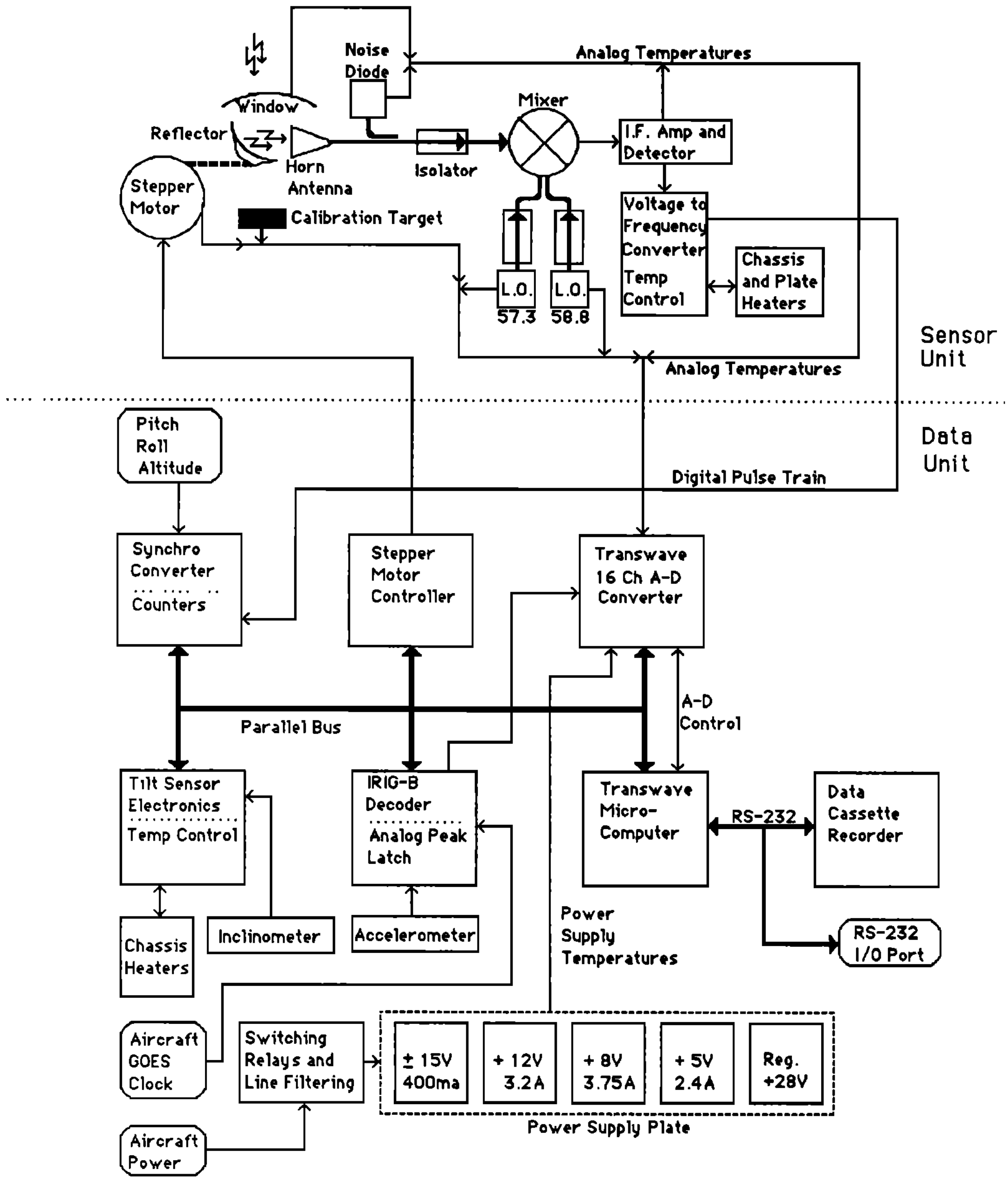

Fig. 5. Block diagrams of the sensor unit (above dotted line) and data unit (below).

wing Spearpod and is connected to the sensor unit by a 6-ft (2-m) cable. This cable handles all communication between the sensor unit and the data unit. Another cable connects aircraft electrical power and aircraft altitude, roll, and pitch signals to the data unit.

The data unit provides the function of controlling the MTP and recording the data on tape. The tape-recording system uses standard Phillips-type digital data cartridges. Approximately 500 kbytes of data can be stored, corresponding to about 8 hours of flight.

The lower portion of Figure 5 shows the relationship between components that will be described in this section. The controlling electronics in the data unit include a microcomputer, a 16-channel analog multiplexer, an analog-to-digital converter, a synchro signal decoder, and a stepper motor controller. The microcomputer was purchased from Transwave Corporation and controls most operations of the MTP using special purpose firmware. The control electronics are mounted on six circuit cards installed in a card cage. The data storage cassette is mounted in the front of the unit, enabling easy access for changing data tapes.

Four power supplies and one regulator provide dc power to MTP. The power supplies operate from the 120-V, 400-Hz aircraft power. The regulator operates from 28-V dc power, which is also provided by the aircraft. All power circuitry is protected from an overvoltage condition.

The microcontroller receives IRIG-B formatted date and time signals from the aircraft GOES satellite receiver for the purpose of synchronizing comparisons of MTP data with other experiments. This time signal is recorded on tape, along with a reading of an MTP battery backup clock.

A vertical accelerometer is installed in the data unit for possible investigation of turbulence characteristics of air that is associated with MTP-measured temperature structures.

Peak excursion circuits monitor the maximum upward and downward excursions during each 14-s observing cycle.

The data unit also contains a tilt sensor for correcting elevation angle commands for changes in aircraft pitch. The tilt sensor, representing pitch, is read prior to the first elevation scan command and is used as an offset to the following 10 elevation commands of that particular cycle. No additional corrections are made for pitch changes that may occur during the following 9.5 s of sky readings. The aircraft pitch synchro signal is also read and recorded each cycle for the purpose of monitoring the quality of the tilt sensor.

Temperature control of the data unit is provided by resistive heaters which are controlled by a circuit similar to the one used in the sensor unit. Power supply temperatures are monitored, and if any monitored location is out of range for three consecutive 14-s cycles, a timer circuit triggers the pilot's console fail lamp.

5. Packaging

MTP was integrated into the NASA ER-2 under the supervision of NASA Ames Research Center and Lockheed Aircraft Corporation, which provides service and maintenance for the ER-2 aircraft. The fairing was designed and constructed by Lockheed in coordination with JPL. The remainder of the instrument was fabricated at JPL with weight, size, and interface constraints defined by NASA Ames and Lockheed. Because the MTP shares the ER-2 Spearpod with other instruments, weight and size were an important consideration in the design of MTP.

The sensor unit is fastened to a forward bulkhead frame, and installation or removal requires that the fairing be removed. Four fasteners attach the sensor unit to the bulkhead using stainless steel inserts, which require safety wiring after installation.

The data unit is mounted to a bracket located in the forward part of the main Spearpod section. The tape transport is accessible through a fold-down flap on the front of the data unit. Retrieval of data tapes is usually accomplished by removing the front Spearpod "nose cone" section.

6. Preflight Tests and Calibration

MTP was tested using chambers that simulate the cold and low air pressure conditions that are encountered on ER-2 flights. The two conditions were tested separately to verify proper performance prior to flight. The initial flight tests were then used to test both extremes simultaneously.

The cold chamber was also used to calibrate MTP under a simulation of flight conditions. System gain was measured using a heated calibration target placed in a sky position of the scan. A repeatable linear (and inverse) relationship was found between system gain and mixer temperature, and this calibration information has been used on subsequent analyses of flight data.

The noise diode output levels were also measured using the hot and ambient calibration targets. The noise diode was determined to produce changes in radiometer output corresponding to 91 and 11 K, for channels 1 and 2, respectively. Thus system gain can be determined from either the "mixer gain versus temperature" relationship or from the change in output level produced by turning on the noise diode.

7. Flight Performance Results

The appendix contains a description of remote sensing concepts that are useful in understanding what MTP measures and how these measured quantities can be converted to the desired atmospheric properties. This section provides an evaluation, based on flight data, of the precisions and accuracies of various MTP-derived atmospheric properties.

The MTP system sensitivity is calculated to be 0.12 and 0.13 K per 255-ms radiometer reading, based on the mixer noise figures, premixer losses (1.5 dB), and IF bandwidths. Because MTP uses a total power radiometer, baseline variations during a 14-s observing cycle can contribute to the measurement uncertainty of the radiometer output. It has been determined that each 255-ms reading has a measurement uncertainty of 0.26 K for both channels. This translates to an uncertainty in each of the sky brightness temperature measurements of approximately 0.33 K. This level of performance has been demonstrated with flight data where outside air temperature fluctuations are small. Hence MTP-derived air temperatures are subject to a 0.33 K component of uncertainty due to hardware sensitivity and baseline characteristics.

Flight data were used to evaluate system gain assump-

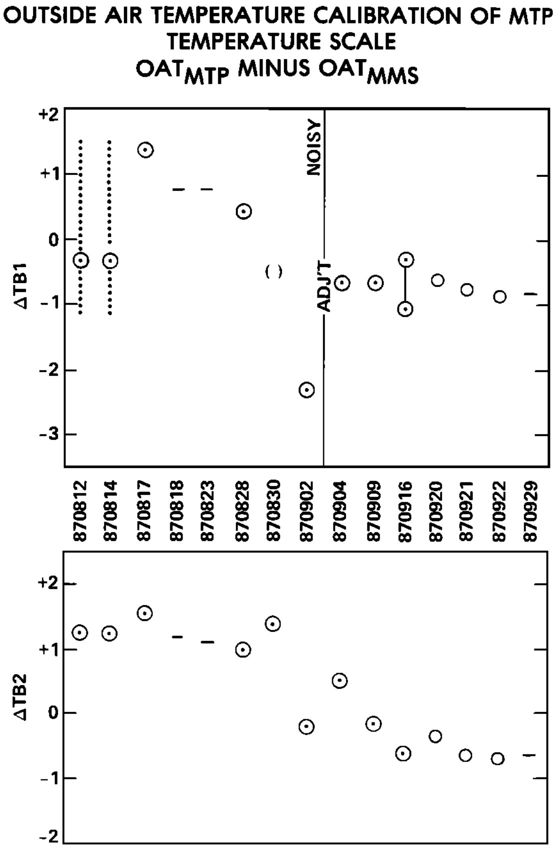

Fig. 6. Calibration adjustments to MTP (units of degrees Kelvin), based on comparisons of the MTP horizon viewing measurements with the MMS (meteorology measurement system) in situ sensor measurement of outside air temperature (OAT). The encircled dots denote valid comparisons. Dashes denote times when MMS data were not available and assumed offsets had to be adopted in order to complete data reduction. The vertical dot pattern denotes a range of uncertainty. Flight dates are indicated in year-month-day format.

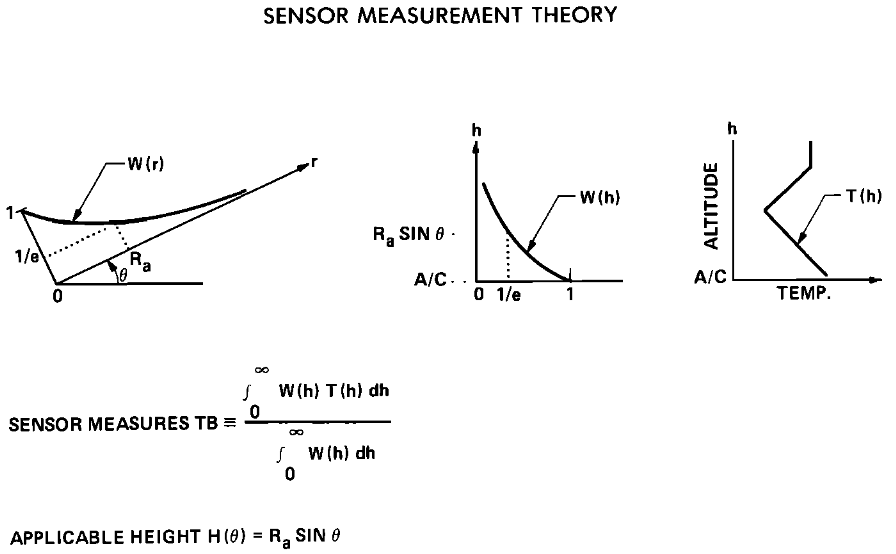

Fig. 7. Remote sensing concepts are illustrated using "weighting function" versus range (left), weighting function versus altitude (middle), and air temperature "source function" versus altitude (right). The MTP sensor observed quantities are TB, defined by the equation (bottom).

tions, using in situ measurements of outside air temperature (OAT) that were measured directly by the meteorological measurement system (MMS) [*Chan et al.*, S. G. Scott et al., manuscript in preparation, 1989]. One of the MTP sky positions is the horizon, yielding a measured brightness temperature which, on average, should be the same as the OAT measured by MMS. Extensive comparisons have been made between the MTP indirectly measured OAT and the MMS directly measured OAT. Offset corrections have been derived for channels 1 and 2 for each flight of the AAOE series. Figure 6 is a plot of these corrections. The rms difference is about 0.7 K for both channels (discounting the "noisy" data of 870902, when channel 1 underwent a failure that required repair).

MTP is not intended to be used for the measurement of OAT because MMS is superior for this task. The OAT comparison serves to validate the properties of MTP that are important, namely, the measurement of lapse rate and structure of air temperature versus altitude profiles. ("Lapse rate" is the vertical gradient of air temperature.) For the measurement of lapse rate it is necessary to know MTP system gains. For example, if lapse rate is to be measured to ±10% (which is our goal), gains should be accurate to the same ±10%. It is therefore possible to use the OAT comparison data in Figure 6 to determine the accuracy of system gains. Considering that the ambient calibration target is usually about 40 K warmer than OAT, a 10% error in gain would produce a 4 K error in the MTP-measured OAT. Although the trends in Figure 6 amount to a total change of about 2 K during the middle of the experiment, the maximum error is about 1 K, which corresponds to a maximum gain error of about 2.5% (i.e., 1/40 = 2.5%). Hence it is concluded that lapse rate is being measured with an accuracy of approximately 2.5%. This is well within the MTP goal of 10%.

Lapse rate accuracy can be verified by determining lapse rate directly from MMS-derived OAT during slow ascents or descents and comparing with MTP-derived lapse rate. This has been done on several occasions, and agreement has always been within the measurement error of such a comparison. For example, on the flight of September 22, 1987, a rare adiabatic layer was encountered during a descent through 55,000 ft (16,764 m, pressure altitude). MMS measured a lapse rate of −9.5 ± 0.5 K/km (after appropriate altitude averaging for comparison with MTP). MTP measured −9.0 ± 0.5 K/km.

Lapse rate is measured by each channel. The layer thickness for lapse rate is determined by the altitude difference between the applicable heights for the −11° and +10° elevation angle readings. For flight at 60,000 ft (18,288 m), for example, the layer thicknesses are 3000 and 1500 ft (914 and 457 m) for channels 1 and 2. These thicknesses vary inversely with air pressure (and are slightly dependent on air temperature). The precision of lapse rate measurements is ±0.20 and ±0.82 K/km, for each 14-s observing cycle, for channels 1 and 2 (for a flight altitude of 60,000 ft). These values are based on actual measurements and may be overestimates due to the presence of real variations in lapse rate that were not accounted for in the estimating procedure. Thicker layers, corresponding to more widely spaced pairs of elevation angles, have better precisions. Accuracy is estimated to be the othogonal sum of about 5% and the precision.

Lapse rate (K/km) can be converted to "pressure gradient of potential temperature" (K/mbar) using standard equations for potential temperature and pressure versus pressure altitude [see *Gary*, 1989]. Potential vorticity is a useful (conservative) property of air parcels, and MTP-derived pressure gradient of potential temperature is one of the two ingredients that are needed for calculating potential vorticity (horizontal wind gradient is the other essential ingredient). Together, MTP and MMS can be used to derive traces of potential vorticity along the ER-2 flight path (see *Hartmann et al.* [1989] for examples of derivations of potential vorticity versus latitude that are based on MMS and MTP observations).

The reader is directed to the companion article [*Gary*, 1989] for samples of MTP-derived lapse rate, pressure gra-

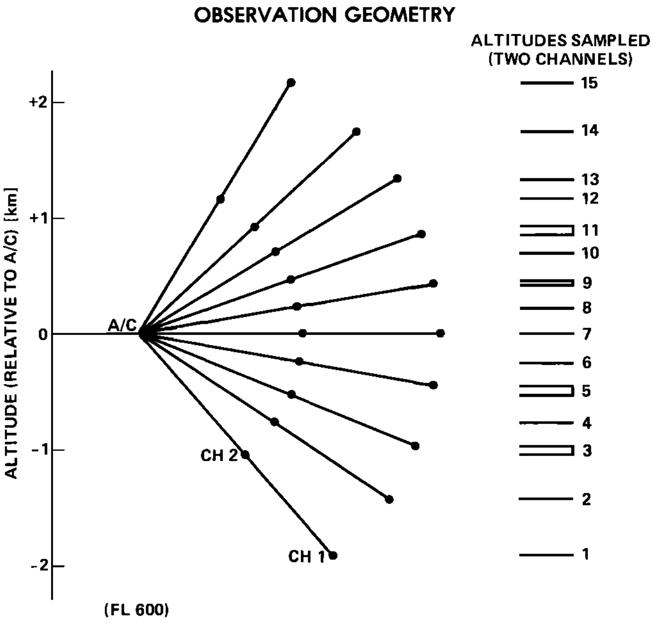

Fig. 8. Observing geometry, showing the applicable range locations in coordinates of altitude versus distance along flight path. The more distant samplings of air temperature are for channel 1. Approximately 15 altitudes are used to represent the slightly redundant groupings of applicable altitudes.

dient lapse rate, altitude temperature profiles, and potential temperature cross sections. Potential temperature cross sections are often the most interesting representation of MTP observables. Atmospheric waves are almost always present in these MTP products, and the potential temperature cross sections are especially interesting during encounters with mountain waves.

APPENDIX: REMOTE SENSING CONCEPTS AND OBSERVING STRATEGY

The spectrum of oxygen molecule absorption in the 60-GHz region consists of a summation of 40 pressure-broadened rotational resonance lines [*Rosenkranz*, 1975]. The resultant spectrum at ER-2 flight levels is an absorption (Np/km) versus frequency plot that exhibits almost 10-fold variations with maxima spaced about 0.7 GHz apart. The MTP IF passbands are tailored to this situation. The double-sided RF passbands are centered on the maxima in the oxygen absorption spectrum. The shape of the passbands, in RF coordinates, approaches zero in a way that assures a minimum of "low oxygen absorption" response. This precaution is intended to minimize the effects of "transparent atmosphere" corrections [*Gary*, 1989].

MTP measures brightness temperature (TB). The radiative equation for TB is described by *Gary* [1989] for the MTP case. Briefly, TB is a weighted average of physical air temperature along the line of sight. The weighting function decreases quasi-exponentially, as depicted in Figure 7 (left). The weighting function can be converted from range coordinates to a height (above aircraft) coordinate (Figure 7, middle). The source function, air temperature, can also be converted from range coordinates to a height coordinate (Figure 7, right). Use of the height coordinate is justified by the fact that surfaces of equal air temperature are almost always level (their slopes are typically within much less than a degree of being level). When the horizontal stratification assumption is not valid, the effect is to shift the MTP profiles a small amount in altitude (with little effect upon shape).

The measured quantity, TB, is shown in Figure 7 to be a weighted average of the source function, T(h). When the source function varies linearly with altitude (i.e., range), a useful property of exponential weighting functions can be

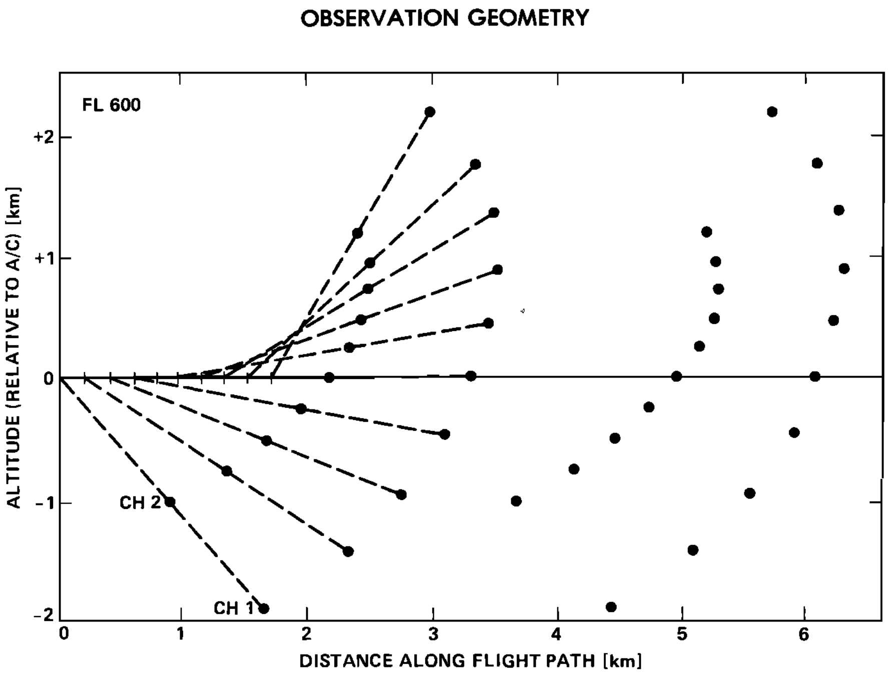

Fig. 9. Same as previous figure, except that aircraft motion has been allowed for. The dashed lines show the 10 sky viewing directions. Two 14-s observing cycles are shown.

exploited: the weighted average equals the value of the source function at the altitude where the weighting function has the value $1/e$ (0.268). This special location is called the "applicable range" (or "applicable height"). For the MTP the applicable range is about 3 km for channel 1 and 1.5 km for channel 2 (for typical flight altitudes). Applicable height, H, is simply the applicable range times the sine of the elevation angle of the observation.

Most of the time, air temperature varies linearly with altitude above and below the aircraft. For these conditions, air temperature versus altitude is obtained from the plot of TB versus applicable height. When this linearity of temperature with altitude is not present, other "retrieval" procedures are available (these are described by *Gary* [1989]). The balance of this discussion will assume that T(h) can be obtained from TB(H).

Figure 8 depicts the locations of the applicable ranges for the MTP. The elevation sequence employed by MTP is −50, −30, −22, −11, 0, +10, +20, +31, +40, +60 degrees. The pattern of points on the inner circle is for channel 2 (for which applicable range is about 1.5 km), and the pattern of points on the outer circle is for channel 1 (for which applicable range is about 3 km). These are the locations where TB measurements can be "assigned." That is, an observing cycle yields 10 channel 1 TB values and 10 channel 2 TB values, and as a first approximation it can be said that these TB values are the air temperatures at the corresponding locations in Figure 8. Note the summary of applicable heights on the right of the figure, showing that there are, in effect, only 15 applicable heights due to the grouping, or overlapping, of certain combinations of channel 1 and 2 applicable heights.

Figure 9 is a replotting of the 20 applicable range locations in the previous figure after allowing for the motion of the ER-2 aircraft during the 14-s observing cycle. The location of "air sample" points is shown for two cycles in this figure. Figure 9 can be thought of as a cross section of a range of altitudes along the flight path of the aircraft. To the extent that the assumptions underlying the conversion of brightness temperatures to air temperatures at these locations is correct, the cross section of sampled points in this figure illustrates the MTP capability for "mapping out" a cross section of air temperature. Iso-air-temperature contours can be drawn upon such a field of points. Atmospheric "waves" can be discerned in this type of MTP product (although waves are more easily identified and studied after the MTP data are converted to potential temperature surfaces). These capabilities are described by *Gary* [1989].

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